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# THE EFFECT OF CATALYST LENGTH AND DOWNSTREAM REACTION DISTANCE ON CATALYTIC COMBUSTOR PERFORMANCE

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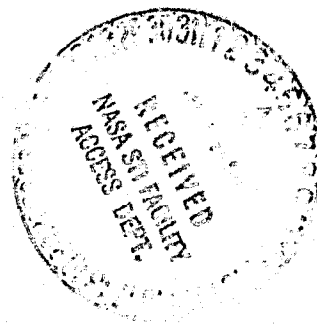
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Prepared for  
Fourth Workshop on Catalytic Combustion sponsored by  
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# **THE EFFECT OF CATALYST LENGTH AND DOWNSTREAM REACTION DISTANCE ON CATALYTIC COMBUSTOR PERFORMANCE**

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## INTRODUCTION

The study reported here was performed to determine how the emissions and pressure drop of a catalytic combustor are affected by changes in the length of the catalytic reactor and in the length available for gas-phase reactions downstream of the catalytic reactor.

A catalytic combustor contains three major components: (1) the fuel-preparation region, in which fuel is injected and premixed with the inlet airstream; (2) the catalytic reactor, in which both surface and gas-phase combustion reactions are initiated; and (3) the downstream gas-phase reactor in which gas-phase reactions continue after initiation in the catalytic reactor. The importance of gas-phase reactions within the catalytic reactor has been discussed in several reports (ref. 1-6). The study of reference 7 also showed that these reactions can be significant downstream of the catalytic reactor. In that study the emissions levels were strongly dependent on the distance downstream from the catalytic reactor to the gas sampling probe. The observations were based on tests of a single length of catalytic reactor at an inlet-air temperature of 800 K. The present paper reports the effects of changing both the catalytic and the gas-phase reactor lengths at an inlet-air temperature of 1000 K.

The work presented here was performed as support for the Department of Energy's Gas Turbine Highway Vehicle Systems Project. Test conditions simulated the combustor conditions in a regenerative automotive gas turbine engine. The inlet-air temperature was 950 - 1000 K, inlet pressure,  $3 \times 10^5$  Pa, reference velocity, 10 and 15 m/s, and the combustor exit temperature was varied from 1200 to 1500 K. Catalysts from three manufacturers were tested in a 12-cm-diameter test duct with catalytic-reactor lengths of 2.5 and 5.4 cm. The effect of gas-phase reactor length was determined by varying the axial location of an exhaust-gas sampling probe from 7.3 to 22.5 cm downstream of the catalyst exit plane. Emissions of CO, CO<sub>2</sub>, UHC, and NO<sub>x</sub> were measured as well as the catalytic-reactor pressure drop.

## APPARATUS

### TEST RIG

The test rig is illustrated in figure 1. It was fabricated from 15.2-cm (6-in nominal) diameter stainless-steel pipe. Carborundum T30R Fiberfrax tube insulation with a 12-cm inside diameter was inserted inside the pipe. The use of internal insulation served to maintain the inlet-air temperature near the preheater discharge value and to reduce the heat loss from the test section. Test-section metal temperatures were calculated to be less than 600 K.

The inlet air was indirectly preheated to approximately 1000 K for all tests. This temperature was measured in a plane just upstream of the fuel-injection location with an array of 12 Chromel-Alumel thermocouples mounted in a flange. The thermocouples were positioned in the duct so that each measured the temperature of an equal-area segment of the cross-section. The average inlet temperature was then calculated as the numerical average of these twelve thermocouples.

The test-section pressure was controlled by a back-pressure valve to  $3 \times 10^5$  Pa for all tests. The test-section-inlet pressure was measured at a tap located in the flange containing the inlet thermocouples. The airflow rate entering the test section was measured by a standard ASME orifice. Fuel flow rate was determined with a Flo-tron linear mass flowmeter. This device employs 4 matched orifices arranged to form a hydraulic Wheatstone Bridge network. A constant-volume pump circulates flow through this network, and the mass flowrate is related to the pressure drop across the network.

### FUEL INJECTOR AND PREMIXING ZONE

A multiple-conical-tube fuel injector of the type developed by Tacina (ref. 8, 9) was used; it is pictured in figure 2. Although it was designed with two sets of fuel tubes for use with either gaseous or liquid fuels, only liquid fuel (no.2 diesel) was used. The array of 21 conical tubes distributed the airflow uniformly over the duct cross section. No. 2 diesel fuel was introduced into the upstream end of each of these cones through a 0.5-mm-inside-diameter fuel tube. The 21 fuel tubes were all the same length (25 cm) to insure that equal fuel flow rates discharged into each of the air cones.

Because of the good initial dispersion of fuel across the duct, excellent fuel-air ratio uniformity is achieved with this type of injector. Tacina (ref. 8) has reported that 23 cm downstream of the fuel-injector inlet the fuel-air ratio profile was uniform to within  $\pm 10$  percent of the mean. The injector tested in reference 8 was designed with 75-percent blockage to the airstream while the injector used in the present study had 87-percent blockage; thus, the performance of the injector used here can be expected to be at least equal to that of reference 8. In the present experiments, the mixing distance from the point of fuel injection to the inlet plane of the catalytic reactor varied from 27.5 cm to 32.5 cm depending on which catalytic reactor was tested. Because the fuel-air ratio profile should already be nearly uniform for even the shortest of the mixing lengths, additional length will have little effect on the fuel-air distribution at the catalytic-reactor inlet and, therefore, little effect on combustion performance.

The pressure drop across the fuel injector was measured with a differential pressure transducer connected between the inlet-pressure tap and one located at the premixing-region thermocouple station.

A single Chromel-Alumel thermocouple was inserted to a depth of about 1 cm into the flow in the premixing zone downstream of the fuel injector. If burning had occurred in the premixing zone, this thermocouple would have triggered a relay to shut off the test-section fuel supply. No burning in the premixer was observed during these tests.

#### CATALYTIC REACTORS

Catalytic reactors were prepared using catalyst elements from 3 manufacturers: Matthey Bishop, Inc. (MBI), Oxy-Catalyst, Inc. (OCI), and UOP, Inc. (UOP). Reactors were either 2.5- or 5.4-cm long depending on whether one or two catalyst elements were used. Figure 1 was drawn with a two-element reactor in the test section. The two elements were each 2.5-cm long and were separated by a 0.31-cm gap. The 2.5-cm-long reactors were made by removing the upstream element from the two-element reactors.

The removal of an upstream element produced a slightly longer premixing-zone length. For the MBI and OCI reactor tests, premixing-zone lengths of 27.5 and 30.3 cm were used with two-element and one-element reactors, respectively. These lengths are shown in figure 1. Tests with the UOP

catalysts were made with premixing-zone lengths of 32.5 and 35.3 cm for the two-element and one-element reactors, respectively.

Table I provides a description of the catalytic reactors tested. The MBI reactors used metal substrates. They were made by Matthey Bishop from Fecralloy foil which was corrugated and wound into a cylinder. The resulting cells had a sine-wave shape, a cell density of 62 per  $\text{cm}^2$ , and an open area of 93 percent of the duct cross-sectional area. The MBI-2.5 reactor was a single element of this substrate with a palladium catalyst. The MBI-5.4 reactor had a second, platinum-catalyst element placed in front of the palladium-catalyst element. Both elements were previously unused.

The two Oxy-Catalyst elements were identical: both used a palladium catalyst on a Corning cordierite square-cell substrate. The open area was 63 percent of the duct cross-sectional area and the cell density was 47 per  $\text{cm}^2$ . The OCI-2.5 reactor used one of these elements and the OCI-5.4 used two. These elements had also been unused before this testing.

The UOP elements also used the Corning cordierite square-cell substrate. Both elements were identical with a proprietary noble-metal catalyst. These elements had been furnace aged a total of 300 hours at a temperature of 1400 K prior to testing.

Single platinum-vs-platinum-13-percent-rhodium thermocouples measured the centerline gas temperature upstream of the reactor and in the gap between the elements. The catalytic reactors were held in place by an array of 12 platinum-vs-platinum-13-percent-rhodium thermocouples at the downstream plane.

The pressure drop across the catalytic reactor was measured with a differential pressure transducer connected between the premixing-zone pressure tap and one located 7.3 cm downstream of the catalytic reactor as shown in figure 1.

#### GAS-PHASE REACTOR

Downstream of the catalytic reactor the combustion products were sampled with a single-point water-cooled probe at the duct centerline. The length of the gas-phase reactor was determined by the axial position of the probe. Data were obtained with the probe at each of four locations: 7.3, 12.4, 17.5 and 22.5 cm downstream of the catalytic reactor. The probe is shown in the 22.5-cm location in figure 1.



The gas-sampling probe was constructed with a single 0.6-cm-inside-diameter sampling passage. The sample line was electrically heated to maintain a temperature of 410-450 K, and it was 18-m long and 0.5 cm in diameter. The continuous-flow samples were analyzed to determine the concentration of nitrogen oxides using a chemiluminescent analyzer, unburned hydrocarbons using a flame-ionization detector, and carbon monoxide and carbon dioxide using nondispersive infrared analyzers.

Temperatures were measured in the gas-phase reactor with platinum-vs-platinum-13-percent-rhodium thermocouples in each of the 4 gas-sampling planes.

## COMPUTATIONS

### REFERENCE VELOCITY

The reference velocity was computed from the measured mass flow rate, the average inlet-air temperature, the duct cross-sectional area ( $113 \text{ cm}^2$ ) and the test-section-inlet pressure ( $3 \times 10^5 \text{ Pa}$ ).

### EMISSION INDEX

The emissions were measured as concentrations in ppm by volume which were converted to emission indexes using the expression

$$(E.I.)_x = C_x \times 10^{-3} \left( \frac{1 + f}{f} \right) \left( \frac{M_x}{M_p} \right)$$

where

$(E.I.)_x$  emission index of specie x,  $\text{g}_x/\text{kg}_{\text{fuel}}$

$C_x$  concentration of specie x, ppm V

$f$  fuel-air weight ratio,  $(\text{kg/s})_{\text{fuel}}/(\text{kg/s})_{\text{air}}$

$M_x$  molecular weight of specie x,  $\text{g}_x/\text{mole}_x$

$M_p$  molecular weight of combustion products,  $\text{g}_{\text{products}}/\text{mole}_{\text{products}}$

### COMBUSTION EFFICIENCY

The difference between the measured and equilibrium emissions of carbon monoxide and unburned hydrocarbons represents available chemical energy which has not been released in the combustion process. For the conditions of this study, the equilibrium emission indexes of unburned hydrocarbons and carbon monoxide are negligible. Furthermore, measured unburned hydrocarbons emissions resulted in emission indexes less than  $0.6 \text{ g HC/kg fuel}$  and, therefore, contributed little to inefficiency. Combustion efficiency was consequently determined from the carbon monoxide emissions alone:

$$\begin{aligned}
 \text{EFF} &= 100 - 0.1 \left( \frac{(\text{HV})_{\text{CO}}}{(\text{HV})_{\text{fuel}}} \right) (\text{E.I.})_{\text{CO}} \\
 &= 100 - 0.0235 (\text{E.I.})_{\text{CO}}
 \end{aligned}$$

where

EFF                    combustion efficiency, percent

$(\text{HV})_{\text{CO}}$             lower heating value of CO,  $1.01 \times 10^7$  J/kg

$(\text{HV})_{\text{fuel}}$            lower heating value of no. 2 diesel,  $4.30 \times 10^7$  J/kg

#### FUEL-AIR RATIO

The fuel-air ratio was determined both from the metered fuel flow and airflow rates and by making a carbon balance from the measured concentrations of CO, CO<sub>2</sub>, and unburned hydrocarbons. The carbon-balance fuel-air ratio had the advantage that it was the local fuel-air ratio at which the emissions data were obtained.

#### ADIABATIC COMBUSTION TEMPERATURE

The adiabatic combustion temperature was calculated from the carbon-balance fuel-air ratio using the equilibrium computer program of reference 10.

## RESULTS AND DISCUSSION

The carbon-balance fuel-air ratios were typically about 95 percent of those determined from the metered fuel flow and airflow rates. This difference probably results from the use of a single gas-sampling probe at the duct centerline, and it indicates that fuel-air premixing, although good, did not result in a perfectly uniform fuel-air ratio over the entire cross section. It also indicates that plug flow continued downstream of the catalytic reactor so that there was little mixing across the duct. Thus, the emissions measured by the probe were determined by local, rather than average, conditions. The local adiabatic combustion temperature is that calculated from the carbon-balance fuel-air ratio, and it will be used in the presentation of results.

No measurable temperature rise along the length of the gas-phase reactor occurred, and the uncorrected catalytic-reactor exit temperatures measured at the centerline were typically only about 25 K less than the adiabatic combustion temperatures. The performance of the various lengths of catalytic and gas-phase reactors will be compared on the basis of the measured emissions and pressure drop.

## EMISSIONS

Allowable emissions from passenger cars have been established by the 1970 Clean-Air Act Amendments which specifies ultimate emissions standards of 0.25 g NO<sub>x</sub>/km, 2.1 g CO/km, and 0.25 g HC/km. Emissions levels are determined by collecting an exhaust sample during a standard metropolitan driving cycle which simulates various transient operating conditions and includes few periods of steady-speed motoring. Thus, there is no simple relationship between the automotive emissions standards and the emissions measured during steady-state tests, such as the ones performed in this study. However, the emissions standards can be transformed into steady-state reference emission indexes by multiplying the standards (in g/km) by an average cycle fuel economy (in km/kg). For this study it was assumed that (1) a gas-turbine powered vehicle could achieve a fuel economy of  $9.35 \times 10^3$  km/m<sup>3</sup> (22 miles/gallon), (2) no. 2 diesel fuel density was 720 kg/m<sup>3</sup>, and (3) the

reference values should be based on only half the emissions permitted by the standards. The third assumption provides some margin for unknown transient and durability effects. The reference emission indexes were thus calculated to be 1.6 g  $\text{NO}_2$ /kg fuel, 13.6 g CO/kg fuel, and 1.6 g HC/kg fuel. The CO reference value represents about 0.32-percent loss in combustion efficiency, and the HC level would result in an additional 0.16-percent loss. The  $\text{NO}_x$  emissions in this study were never more than 0.25 g  $\text{NO}_x$ /kg fuel, and unburned hydrocarbons were below 0.6 g HC/kg fuel. Therefore, only the carbon monoxide emissions will be examined in detail.

The carbon monoxide emission indexes for each of the six catalytic reactors are plotted in figure 3(a) - (f) as a function of the adiabatic combustion temperature. The results for the four different gas-phase reaction distances are given in each figure for reference velocities of 10 m/s (solid curves) and 15 m/s (dashed curves). The combustion efficiency which corresponds with each CO emission index is shown as a second ordinate.

Results for the MBI-2.5 reactor are given in figure 3(a). Carbon monoxide levels decreased nearly two orders of magnitude when the adiabatic combustion temperature was increased by 150 - 200 K for all conditions. For both 10- and 15-m/s reference velocities, an increase in the gas-phase-reactor length from 7.3 to 22.5 cm also produced approximately a two-orders-of-magnitude reduction in CO at a fixed adiabatic combustion temperature. Emissions were below the 13.6-g-CO/kg-fuel reference for adiabatic combustion temperatures greater than 1265 K for the 22.5-cm-long gas-phase reactor at a reference velocity of 10 m/s. When the velocity was increased to 15 m/s, the same 22.5-cm-long gas-phase reactor required temperatures of at least 1340 K to achieve the reference level. For the 7.3-cm-long gas-phase reactor at 15 m/s, a temperature of nearly 1500 K was required.

When the catalytic-reactor length was increased to 5.4 cm, the CO emissions, shown in figure 3(b), were lower than those of the 2.5-cm-long catalytic reactor at any given condition. For a 7.3-cm-long gas-phase reactor and a reference velocity of 15 m/s, the adiabatic combustion temperature required to achieve the reference CO level was reduced from nearly 1500 K for the MBI-2.5 catalytic reactor (fig. 3(a)) to 1400 K for the MBI-5.4 reactor (fig. 3(b)). For the same 7.3-cm gas-phase reactor length at 10 m/s the

MBI-2.5 reactor (fig. 3(a)) required an adiabatic combustion temperature of 1365 K to reach the reference level of CO emissions, while the MBI-5.4 reactor (fig. 3(b)) required only 1345 K.

The same general trends were observed for the OCI-2.5 and OCI-5.4 catalytic reactors as shown in figure 3(c) and 3(d), respectively, and for the UOP-2.5 and UOP-5.4 catalytic reactors as shown in figure 3(e) and 3(f).

#### MINIMUM OPERATING TEMPERATURE

The minimum operating temperature is defined as the adiabatic combustion temperature at which all the emissions goals are met. As noted previously, in this study the minimum operating temperature could be determined solely from the CO emissions since unburned hydrocarbons were always well below the reference level. The minimum operating temperature was determined for all of the test configurations by noting the adiabatic combustion temperature at which each of the CO curves of figure 3 crossed the reference emission index level.

The effect of the total catalytic-plus-gas-phase-reactor length on the minimum operating temperature for all six catalytic reactors can be seen in figure 4. The open symbols and solid lines represent the minimum operating temperatures of the 2.5-cm-long catalytic reactors, while the solid symbols and dashed lines are for the 5.4-cm-long catalytic reactors. Results are given at reference velocities of 10 m/s and 15 m/s for each catalytic-reactor length.

From figure 4 it can be seen that within the experimental accuracy there was no difference between the results for the MBI, OCI, and UOP reactors of the same length. The fact that the UOP reactors, after having been aged for 300 hours at 1400 K, performed as well as the unaged catalysts suggests a potential for a long lifetime. The duration of these tests (typically 5-6 hours per reactor) was insufficient to determine if the MBI and OCI catalysts would also be durable for long periods.

Figure 4 also shows that for each reference velocity and catalytic-reactor length, an increase in the total catalytic-plus-gas-phase-reactor length resulted in a lower value for the minimum operating temperature. For example, for single-element reactors tested at a reference velocity of 10 m/s (solid curve with open circles), an increase in total length from 10 cm to 13 cm

reduced the minimum operating temperature from 1375 K to 1335 K. Similar reductions were also observed with the 5.4-cm-long catalytic reactors (dashed line, solid symbols) and at 15 m/s reference velocity (square symbols).

The reduction of 40 K in minimum operating temperature in the above example was achieved by increasing the gas-phase-reactor length with a constant catalytic-reactor length. If the total length had been increased from 10 cm to 13 cm by increasing the catalytic-reactor length from 2.5 cm to 5.4 cm with a constant gas-phase-reactor length, the minimum operating temperature for a reference velocity of 10 m/s would have decreased by 50 K (from 1375 K to 1325 K). Thus, the catalytic-length effect was slightly greater than the gas-phase-length effect at a velocity of 10 m/s.

At a reference velocity of 15 m/s the catalytic-length effect on minimum operating temperature was much greater than the gas-phase-length effect. The increase in total length from 10 cm to 13 cm which was achieved by increasing the gas-phase-reactor length while maintaining catalytic-reactor length constant at 2.5 cm can be seen from figure 4 (solid curve, open squares) to have reduced the minimum operating temperature by 50 K (from 1490 K to 1440 K). When the same increase in total length was obtained by increasing the catalytic-reactor length from 2.5 cm to 5.4 cm while maintaining a constant gas-phase-reactor length, the minimum operating temperature was decreased by 100 K (from 1490 K to 1390 K). At a velocity of 15 m/s, then, there was a clear advantage, in terms of minimum operating temperature, to the use of a longer catalytic reactor as opposed to the use of a longer gas-phase reactor.

Because residence time is a fundamental variable which includes both length and velocity, it is of interest to analyze these results again on the basis of changes in residence time. The minimum operating temperatures have been plotted again in figure 5 to show the effect of the total combustion residence time. The residence time was calculated from the total catalytic-plus-gas-phase-reactor length by assuming that (1) the combustion temperature increased linearly within the catalytic reactor so that the adiabatic combustion temperature was reached at the exit of the first element for either one- or two-element reactors, (2) the gas temperature throughout the rest of the system was constant and equal to the adiabatic combustion temperature, (3) the pressure was constant, and (4) the open area of the catalytic-reactor channels was 93 percent of the duct cross-sectional area for the MBI reactors

and 63 percent for OCI and UOP reactors. The residence times of the flow through the various catalytic reactors at each of the two reference velocities have also been indicated in figure 5 to assist in determining the effects of catalytic-reactor residence time. The accuracy of the calculated residence times was dependent on experimental measuring error as well as the validity of these assumptions, and the values shown in figure 5 were estimated to be accurate to within  $\pm 5$  percent.

Figure 5 shows that the minimum operating temperature could be decreased by providing more total combustion residence time. In addition to this general trend, the results were segregated according to the catalytic-reactor residence time into two curves. Catalytic-reactor residence times ranged from 0.9 ms to 4.1 ms for this experiment. The configurations which had the lowest catalyst residence times (0.9 to 1.3 ms) also had the highest minimum operating temperatures. When the catalytic-reactor residence time was greater than 1.4 ms, minimum operating temperatures were about 50 K lower than those for catalyst residence times of 0.9 to 1.3 ms. However, no further decrease in minimum operating temperature was obtained when catalytic-reactor residence times were increased to values as high as 4.1 ms at a constant total combustion residence time. Thus, for these experimental conditions, gas-phase residence time was as effective as catalytic residence time in determining minimum operating temperature if the catalytic-reactor residence time was at least 1.4 ms. By this time, apparently, gas-phase reactions were sufficiently established within the catalytic reactor channels that additional catalyst was unnecessary.

#### PRESSURE DROP

In addition to low-emissions capability, it is necessary for gas-turbine combustors to operate with minimal pressure loss. The pressure-drop measurements made in the present study do not necessarily provide values which would be the same as those of a practical catalytic combustor; however, they do indicate what contribution can be expected from the catalytic components. The pressure drop as a percentage of the total upstream pressure is shown as a function of the adiabatic combustion temperature for the MBI reactors in figure 6(a), for the OCI reactors in figure 6(b), and for the UOP reactors in figure 6(c).



The measured pressure loss increased gradually with increasing adiabatic combustion temperature. The two-element MBI and OCI reactors had pressure losses which varied from 0.7 to 0.95 percent at 15-m/s reference velocity and 0.3 to 0.6 percent at 10 m/s. The UOP reactor produced lower values. The losses measured across one-element reactors were typically about half the values for two-element reactors. The flow in the catalyst channels was laminar for all conditions studied and the measured effect of velocity on pressure drop was consistent with a laminar-flow friction-loss mechanism dominating over entry and exit losses. The pressure drop in the gas-phase reactor was calculated to be less than  $2 \times 10^{-3}$  percent for the test conditions of this study.

The pressure drop across the multiple-conical-tube fuel injector was typically about 1 percent at a reference velocity of 10 m/s and 2 percent at 15 m/s. These losses are higher than would be acceptable for many practical applications; however, the fuel-injector blockage (87 percent) was greater than was necessary. Tacina (ref. 8) achieved an excellent fuel-air ratio profile from another injector of the same type which was designed with less blockage (75 percent). He reported pressure losses to be only 0.25 percent at a velocity of 10 m/s and 1 percent at 20 m/s.

For a low-blockage multiple-conical-tube fuel injector and a two-element catalytic reactor, the combined pressure drop can be predicted to be about 0.75 percent at a reference velocity of 10 m/s and about 2 percent at 20 m/s. Even at the higher velocity, this loss is acceptable for practical combustor applications.

## CONCLUDING REMARKS

This study demonstrated that a 2.5-cm length of catalytic reactor followed by a 7.3-cm length of gas-phase reaction distance is adequate to achieve acceptable emissions at the following conditions: an inlet-air temperature of 1000 K, a pressure of  $3 \times 10^5$  Pa, a reference velocity of 10 m/s, and an adiabatic combustion temperature of 1400 K. Acceptable emissions could also be obtained at adiabatic combustion temperatures lower than this by increasing either the catalytic-reactor length or the gas-phase reaction distance downstream of the catalytic reactor. In other words, the minimum operating temperature (defined as the lowest adiabatic combustion temperature at which the emissions are within acceptable levels) decreased with increasing total combustion (catalytic-plus-gas-phase-reactor) residence time.

The relative time spent by the combustion gases in the catalytic and in the gas-phase reactors was shown to affect the minimum operating temperature only if the catalytic-reactor residence time was less than 1.4 ms. For catalyst residence times greater than 1.4 ms, apparently, gas-phase reactions were well established within the catalytic-reactor channels, and there was no further contribution of surface reactions. Thus, a catalytic combustor designed to operate at the conditions of this study would need to incorporate no more catalytic-reactor length than was necessary to provide a 1.4-ms catalyst residence time. Advanced automotive gas turbine engines may have combustor inlet temperatures as high as 1340 K. For these inlet-air temperatures, even less catalytic-reactor residence time may be required, and therefore, it may be possible to increase reference velocities or reduce catalytic-reactor length without penalizing emissions performance. Alternatively, lower catalyst loadings or substrate cell densities below the  $47\text{--}62 \text{ cells/cm}^2$  used in this study may be possible. Further evaluation is required to establish the effect of higher inlet-air temperatures on the required catalytic-reactor residence time.

The data reported were obtained at only one pressure,  $3 \times 10^5$  Pa. While this value is representative of part of the automotive-gas-turbine range ( $1.5 \times 10^5$  to  $5 \times 10^5$  Pa), data are also needed at higher and lower pressures before general conclusions can be drawn about required lengths of catalytic reactors, catalyst loadings, or substrate geometries.

Operation of catalysts at high temperatures for extended periods of time will, of course, result in a loss of catalyst activity. Although one catalyst included in these tests had received a 300-hour furnace aging at 1400 K and showed no disadvantage relative to unaged catalysts, longer combustion aging at higher temperatures will be experienced by catalysts used in catalytic combustors. The subsequent loss of catalyst activity, the changes it will produce in the performance of the catalytic reactor, and its effect on the conclusions of this study cannot be predicted. As catalyst development continues to produce catalysts capable of higher and higher maximum operating temperatures, it is possible that little effect of aging would be seen during the typical lifetime of an automobile. On the other hand, it may be necessary to overdesign the catalytic reactor by making it longer than the initial catalytic activity would necessitate.

Additional work is clearly required to complete the process of establishing design information for automotive gas-turbine catalytic combustors.

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TABLE I . DESCRIPTION OF CATALYTIC REACTORS

Reactor	No. of Elements	Reactor Length, cm	Upstream Element			Downstream Element			Manufacturer
			Catalyst Material	Catalyst Loading, kg/m <sup>3</sup>	Substrate (see Table Ia)	Catalyst Material	Catalyst Loading, kg/m <sup>3</sup>	Substrate (see below)	
MBI-2.5 MBI-5.4	1	2.5	-	-	-	Palladium	7.1	1	Matthey Bishop Matthey Bishop
	2	5.4	Platinum	5.3	1	Palladium	7.1	1	
OCI-2.5 OCI-5.4	1	2.5	-	-	-	Palladium	3.6	2	Oxy-Catalyst Oxy-Catalyst
	2	5.4	Palladium	3.6	2	Palladium	3.6	2	
UOP-2.5 UOP-5.4	1	2.5	-	-	-	Noble Metal	*	2	UOP UOP
	2	5.4	Noble Metal	*	2	Noble Metal	*	2	

The MBI and OCI reactors were unaged.

The UOP elements had been exposed to 1400K air in a furnace for 300 hours.

\* Proprietary

TABLE Ia. SUBSTRATE DESCRIPTION

Substrate	Manufacturer	Material	Cell Shape	Cell Density, cells/cm <sup>2</sup>	Open Area, percent
1	Matthey Bishop Corning	Fecralloy cordierite	Sine wave square	62	93
2				47	63

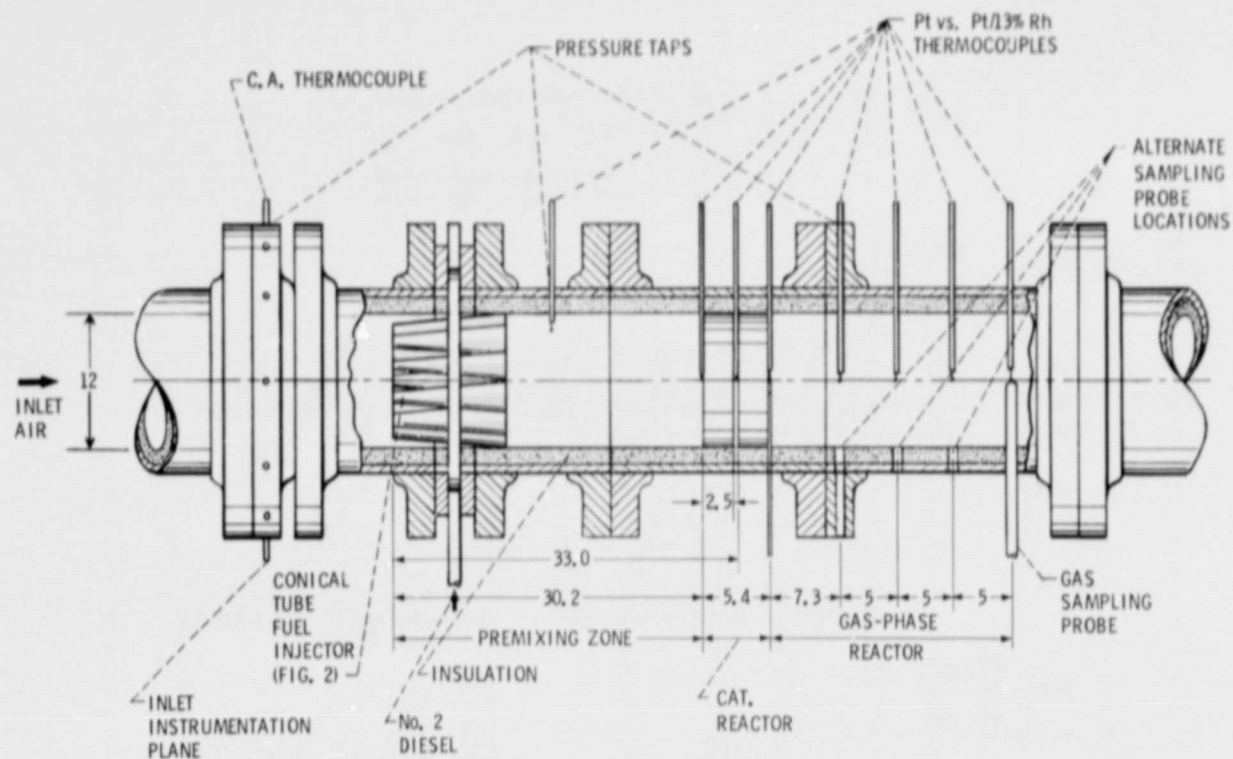


Figure 1. - Test section. (Dimensions in cm.) 5.4-cm-long catalytic reactor shown.

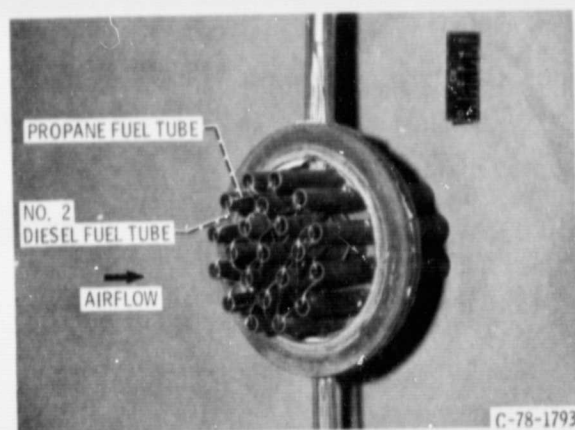


Figure 2. - Multiple conical tube fuel injector.

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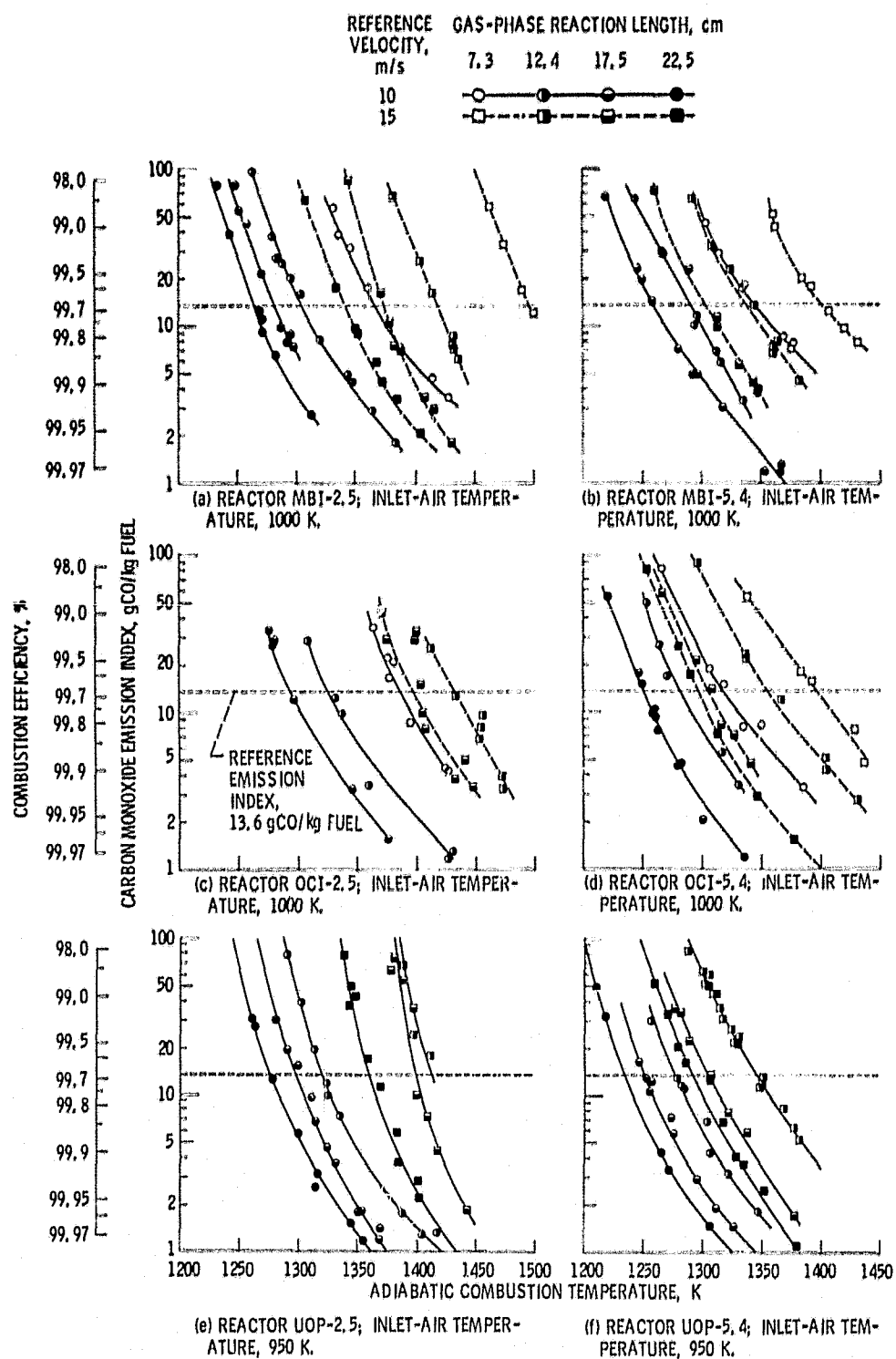


Figure 3. - Carbon monoxide emissions. Pressure,  $3 \times 10^5$  Pa.



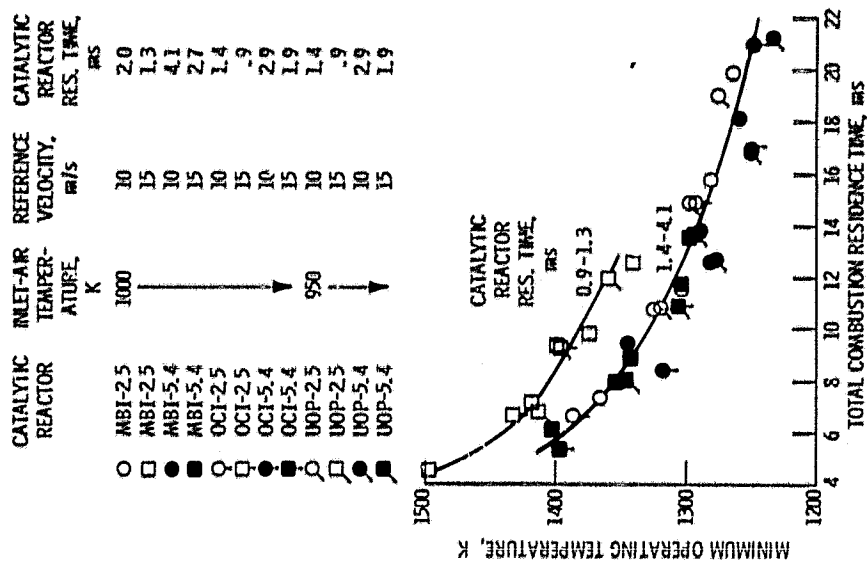


Figure 5. - Effect of residence time on minimum operating temperature. Pressure,  $3 \times 10^5$  Pa.

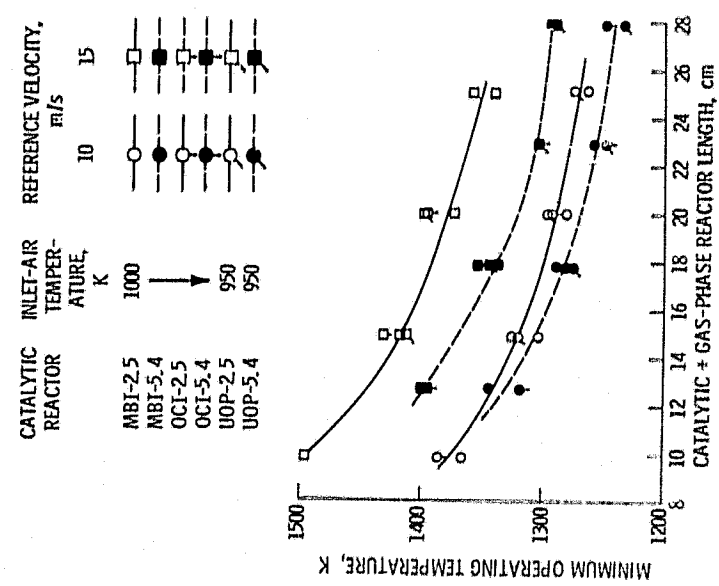


Figure 4. - Effect of combustion length on minimum operating temperature. Pressure,  $3 \times 10^5$  Pa.

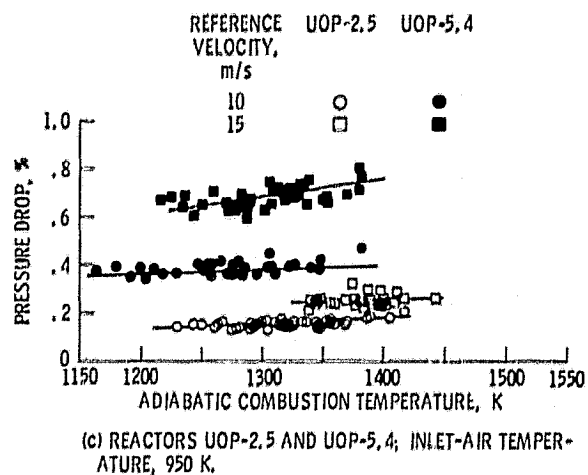
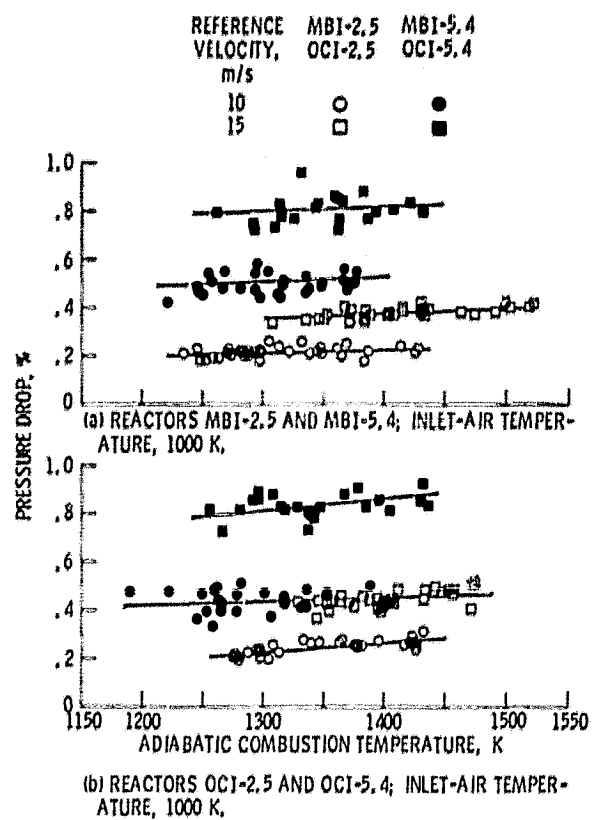


Figure 5. - Catalytic reactor pressure drop. Pressure,  $3 \times 10^5$  Pa.

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16. Abstract A study was made to determine the effects on catalytic combustor performance which resulted from independently varying the length of a catalytic reactor and the length available for gas-phase reactions downstream of the catalyst. Monolithic combustion catalysts from three manufacturers were tested in a combustion test rig with no. 2 diesel fuel at an inlet-air temperature of 1000 K, a pressure of $3 \times 10^5$ Pa, reference velocities of 10 and 15 m/s, and adiabatic combustion temperatures of 1200 to 1500 K. Catalytic reactor lengths of 2.5 and 5.4 cm, and downstream gas-phase reaction distances of 7.3, 12.4, 17.5, and 22.5 cm were evaluated. Measurements of carbon monoxide, unburned hydrocarbons, nitrogen oxides, and pressure drop were made. The catalytic-reactor pressure drop was less than 1 percent of the upstream total pressure for all test configurations and test conditions. Nitrogen oxides and unburned hydrocarbons emissions were less than 0.25 g NO <sub>2</sub> /kg fuel and 0.6 g HC/kg fuel, respectively. The minimum operating temperature (defined as the adiabatic combustion temperature required to obtain carbon monoxide emissions below a reference level of 13.6 g CO/kg fuel) ranged from 1230 K to 1500 K for the various conditions and configurations tested. The minimum operating temperature decreased with increasing total (catalytic-reactor-plus-downstream-gas-phase-reaction-zone) residence time but was independent of the relative times spent in each region when the catalytic-reactor residence time was greater than or equal to 1.4 ms.			
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